

# The Highly Flattened Dark Matter Halo of NGC 4244

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## Abstract.

In a previous paper (Olling 1995) a method was developed to determine the shapes of dark matter halos of spiral galaxies from an accurate determination of the rotation curve, the flaring of the gas layer and the velocity dispersion in the H I. Here I report the results for the almost edge-on Scd galaxy NGC 4244 (Olling 1996a, 1996b).

The observed flaring of the H I beyond the optical disk puts significant constraints on the shape of the dark matter halo, which are almost independent of the stellar mass-to-light ratio. NGC 4244's dark matter halo is found to be highly flattened with a shortest-to-longest axis ratio of  $0.2^{+0.3}_{-0.1}$ . If the dark matter is disk-like, the data presented in this paper imply that the vertical velocity dispersion of the dark matter must be 10% - 30% larger than the measured tangential dispersion in the H I.

## 1. Introduction

Although rotation curves of spiral galaxies have been used as evidence for the presence of dark matter (DM), little is known about the nature, extent and actual distribution of the DM in individual galaxies (e.g., van Albada *et al.* 1985; Lake & Feinswog 1989). As measurements of the equatorial rotation curve probe the potential in only one direction, they provide no information about the shape of the DM halos.

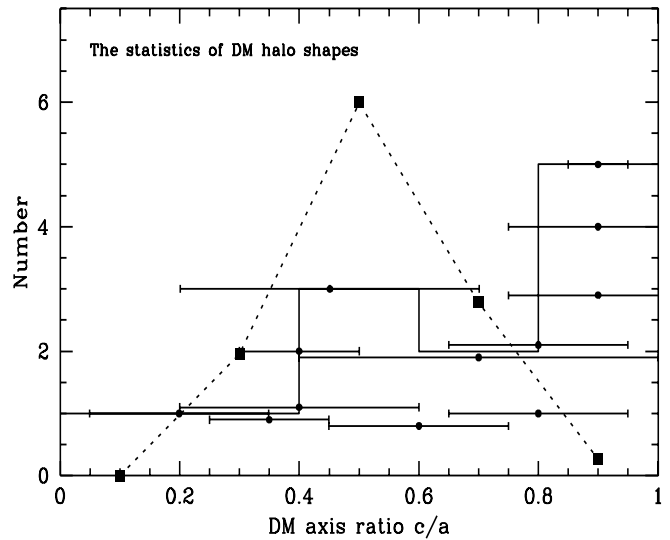
Several methods have been used to determine the shapes of dark matter halos. Analyzing the warping behavior of H I disks, Hofner & Sparke (1994) conclude that only one (NGC2903) of the five systems studied requires a DM halo as flattened as E4<sup>1</sup>. On the other hand, in studies of polar ring galaxies (Sackett & Sparke 1990; Sackett *et al.* 1994; Sackett & Pogge 1995) substantially flattened DM halos are found (E6-E7 for NGC 4650A, E5 for A0136-0801). The shape of the dark halo of the Milky Way has been estimated (E0 - E7) from the kinematics of extreme Population II stars (Binney, May & Ostriker 1987b;

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<sup>1</sup>A spheroidal system with shortest-to-longest axis ratio  $c/a$  ( $q_\rho$ ) of the density contours has a shape  $En$ , with  $n$  such that  $q_\rho = 1 - n/10$

Sommer-Larsen & Zhen 1990; van der Marel 1991; Amendt & Cuddeford 1994). From the dynamics of the precessing dusty disk of the S0 galaxy NGC 4753 Steiman-Cameron *et al.* (1992) infer a rather round DM halo (E1). Buote & Canizares (1996a, 1996b) used the shape of X-ray isophotes to infer that the dark halos of NGC 1332 and NGC 720 are moderately flattened (E5.5 and E6, respectively). Cold dark matter galaxy formation simulations which include gas dynamics tend to produce rather oblate DM halos (Katz & Gunn 1991; Udry & Martinet 1994), with an intrinsic flattening distribution peaked at  $q_\rho = c/a = 0.5 \pm 0.15$  (Dubinski 1994). The current state of affairs is summarized in Fig. 1.

Fig. 1. A histogram of the known DM halo shapes. The Dotted line and the filled squares represent the theoretical prediction. The points with error bars represent the individual galaxies. Note the discrepancy between the results from the warping-gas-layer method (right-most bin) and the other methods.



Van der Kruit (1981) pioneered the use of flaring measurements to determine the mass of stellar disks, and found that the scale length of the total matter (luminous plus dark) was similar to the scale length of the light distribution and concluded that the mass-to-light ratio does not vary significantly with radius. This method could not be applied to NGC 4244 since no reliable flaring information is obtained for the inner parts of the galaxy.

In a previous paper, Paper I (Olling 1995), a method was developed to determine the shape of the dark matter halo from the gaseous velocity dispersion and the radial variation of the thickness of gas layers (flaring). This is accomplished by comparing the measured flaring with that expected from a self-gravitating gaseous disk in the axisymmetric potential due to the stellar disk and (flattened) DM halo. That the shape of the dark halo influences the width of the gas layer can be easily understood. Consider a round halo, with a certain density distribution, then squeeze it along the vertical axis. Consequently, the densities as well as the exerted gravitational forces will increase, resulting in a thinner HI disk and higher rotation speeds. In order to keep the same rotation curve, one has to deform the DM-halo in a very specific way (Paper I) as a result of which the DM-halo densities (at large distances) will be roughly inversely proportional to the flattening  $q_\rho$ . Since the thickness of the gas layer beyond the optical disk is proportional to  $1/\sqrt{\rho_{DM}}$  (Paper I; cf. Eqn. [1] with  $K_z z \approx 4\pi G \int dz' \rho_{DM}(z')$ ), the halo flattening  $\propto$  (width of the gas layer)<sup>2</sup>.

Below I apply the method to the galaxy NGC 4244 for which the basic parameters were determined in Paper II (Olling 1996a).

## 2. The Method

Assuming that the gaseous velocity dispersion ( $\sigma_{\text{gas}}$ ) does not vary with height above the plane ( $z$ ), the gaseous density distribution ( $\rho_{\text{gas}}(z)$ ) can be calculated from the equation of hydrostatic equilibrium:

$$\sigma_{\text{gas}}^2 \frac{d \ln \rho_{\text{gas}}(z)}{d z} = -K_z(z) , \quad (1)$$

where the vertical force ( $K_z$ ) is calculated by integrating over the density distribution of the galaxy ( $\rho_{\text{tot}}(R, z)$ ) :

$$K_z(R, z) = G \int_0^\infty r dr \rho(r, 0) \int_{-\infty}^\infty dw \rho_{\text{tot}}(r, w) \int_{-\pi}^\pi \frac{d}{dz} \frac{d\theta}{|\mathbf{s} - \mathbf{S}|} , \quad (2)$$

with  $\mathbf{s} = \{r, w\}$  and  $\mathbf{S} = \{R, z\}$ . Although more complicated than the more commonly used local approximation (where the vertical force is calculated from the local density distribution), this global approach has no problems in those regions where the local approach fails: in the inner parts of the galaxy where the rotation curve rises steeply and in the region where the (stellar) density distribution is truncated (Paper I). I incorporate three components in the global mass model : 1) a double exponential stellar disk with constant scale-height, 2) a non-singular flattened isothermal DM-halo with core radius  $R_c(q_\rho)$  and central density  $\rho_0(q_\rho)$  (Paper I), and 3) a gaseous disk. Three iterations are required to determine  $\rho_{\text{gas}}(R, z)$  accurately.

The dependency of  $R_c$  and  $\rho_0$  upon  $q_\rho$  is such that the rotation curve of the flattened DM halo is practically indistinguishable from its round equivalent (Paper I). Of course, the true DM-halo density distribution may be different (e.g., Navarro, Frenk, & White 1996). However, for roundish DM distributions the vertical force is roughly proportional to the radial force ( $K_z = z / \sqrt{z^2 + R^2} F_{\text{tot}} \approx z / R F_R \propto \frac{z}{R} V_{\text{obs}}^2$ ), which is the same for all disk-AnyRoundDarkHalo combinations that reproduce the observed rotation curve: for a given rotation curve, the width of the gas layer is independent of the radial distribution of the DM. The flattening of the DM halo introduces a  $\sim \sqrt{q_\rho}$ -dependence on the thickness of the gas layer, which might be slightly different for various radial distributions.

Comparing the thickness of the gas layer beyond the optical disk with model flaring curves, calculated for a series of models with varying halo flattening, then yields the halo shape.

## 3. Results

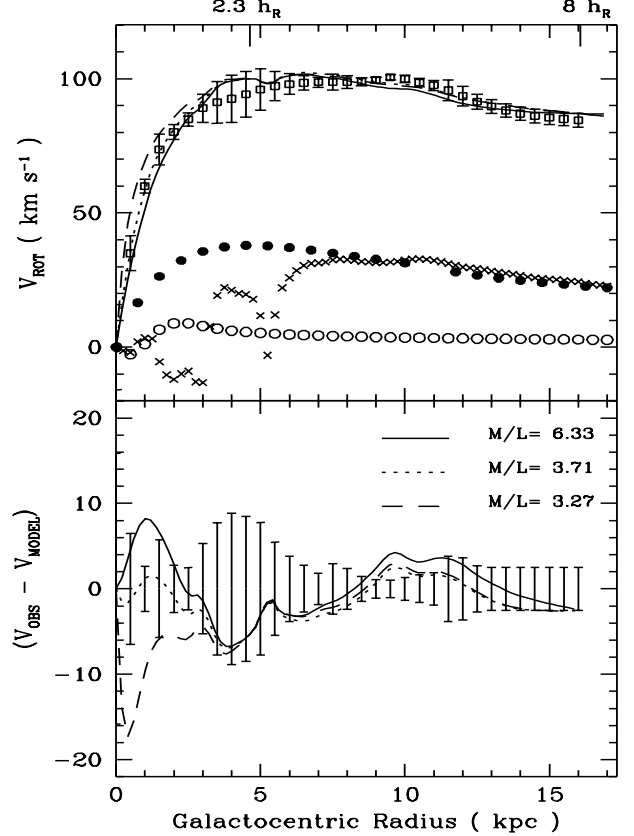
The almost edge-on, nearby Scd galaxy NGC 4244 was observed for about 14 hours with the VLA<sup>2</sup> in B-, C-, and D- array configuration. These ob-

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<sup>2</sup>The VLA of the National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

servations were used to determine the gaseous velocity dispersion, the thickness of the gas layer, and the rotation curve (Fig. 2). The rotation curve of NGC declines from 5 optical scale-lengths to the last measured point (at  $8h$ ) in Keplerian fashion (Olling 1996a). While compact fast rotating galaxies ( $V_{max} \geq 180 \text{ km s}^{-1}$ ) are known to have declining rotation curves (Casertano & van Gorkom 1991; Persic Salucci, & Stel 1996), NGC 4244 is the only low mass galaxy ( $V_{max} \approx 100 \text{ km s}^{-1}$ ) for which the rotation curve falls.

Fig. 2. The top panel shows 3 disk-halo decompositions of the observed rotation curve (squares with error bars) into components due to the gaseous disks (H I, crosses; H<sub>2</sub>, open circles), a component due to the stellar disk ( $M/L_B = 1$ ; filled circles) and a DM component. The individual stellar and DM components are not shown here. The best fit ( $M/L = 3.71$ ,  $R_c = 0.65 \text{ kpc}$ ,  $\rho_0 = 233 \text{ m}M_\odot/\text{pc}^3$ ,  $\chi^2/DF = 0.864$  with 32 degrees of freedom, dotted line) as well as those models with a reduced  $\chi^2$  value 1.0 larger are shown:  $M/L = 6.33$ ,  $R_c = 13$ ,  $\rho_0 = 1.43$  (full line), and  $M/L = 3.27$ ,  $R_c = 0.28$ ,  $\rho_0 = 1300$  (dashed line). The optical scale-length ( $h_R$ ) and the truncation of the stellar disk at  $R_{max}$  are also indicated.

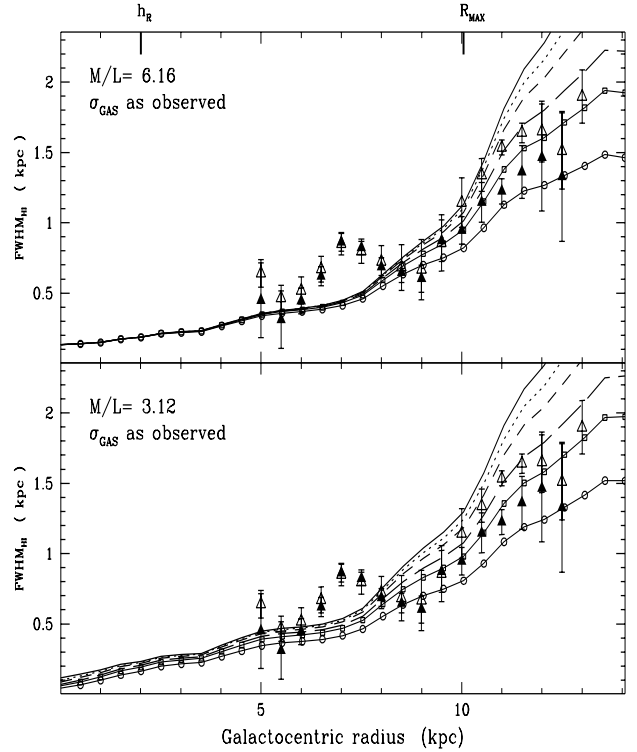


I developed a new technique to determine simultaneously the thickness and inclination of the H I layer for galaxies at an inclination  $\geq 60$  degrees which uses about half the spectral line channels of the H I data set (Paper II). The resulting flaring measurements for NGC 4244 are presented in Fig. 3 for two cases. An upper limit to the thickness of the gas gayer is found by assuming a constant inclination of  $84.5^\circ$  (open triangles), while incorporating the slight warp into the analysis yields the best values for the flaring (filled triangles).

Comparing the observations with the model flaring curves (drawn lines) I conclude that the DM halo of NGC 4244 is highly flattened:  $q_\rho = 0.2 \pm 0.1$ , (Olling 1996b, hereafter referred to as Paper III). The dark halo of NGC 4244 is the flattest reported to date, furthermore it lies at the extreme end of the theoretical predictions (Fig. 1). Is it possible that some systematic effect plays a role and that NGC 4244's DM halo is less flattened? The most obvious candidate

being an error in the assumed inclination (Fig. 3, open triangles). However, the warp is very similar on both sides of the galaxy (Paper II), so that this is not likely. Another candidate is the presence of an extra galactic radiation field (EgRF) which would ionize the H I layer from above and decrease the width of the *neutral* gas layer (Maloney 1993): if the EgRF is as strong as the  $2\text{-}\sigma$  upper limit reported by Vogel *et al.* (1995), we would infer a less flattened DM halo with  $q_\rho = 0.5 \pm 0.2$  (Paper III). Thirdly, non-thermal pressure gradients could be important. However, Bicay & Helou (1990) find that cosmic rays are closely related to sites of star formation so that cosmic ray pressure (CRP) is not likely to be important beyond the optical disk. If CRP *is* important it would require an even *denser*, i.e. *flatter* DM halo. Another possibility is that the gaseous velocity dispersion tensor is anisotropic: if the vertical velocity dispersion is smaller than the planar dispersion measured the DM halo would be rounder than inferred above. There is no observational evidence that such might be the case. Furthermore, because the Interstellar Medium (ISM) is likely to be in the warm neutral phase due to the low pressure (Maloney 1993), the short collision times ( $\leq 10^5$  year) preclude any anisotropy in the velocity dispersion tensor.

Fig. 3. The measured gas layer widths (open and filled triangles for fixed inclination and warp-included case, respectively). The model curves (drawn lines) correspond to different halo shape:  $q_\rho = 1.0, 0.7, 0.5, 0.3, 0.2$ , and  $0.1$  from top to bottom. The measured gaseous velocity dispersions (Paper II) were used in the model calculations. Using both inclination cases I find:  $q_\rho = 0.2^{+0.3}_{-0.1}$ . The mass-to-light ratio of the stellar disk is not constrained by these flaring measurements.



Taking systematic errors due to inclination and ionization effects into account, we conclude that the DM halo of NGC 4244 is significantly flattened, with  $q_\rho = 0.2^{+0.3}_{-0.1}$ .

#### 4. An Alternative Explanation ?

Rich clusters of galaxies contain  $\sim (10 \pm 5)h^{-1.5}$  % (by mass) hot X-ray emitting gas (e.g., Briel *et al.* 1992; Mushotzky *et al.* 1995), with  $h$  the normalized Hubble constant ( $h = H_0/(100 \text{ km s}^{-1}\text{Mpc}^{-1})$ ). If these clusters are a “fair sample” of the universe as a whole, then the average mass-to-light ratio of a cluster baryon ( $M/\mathcal{L}_{\text{Bar,cl}}$ ) lies in the range  $(32 - 48)h^{-0.5}$ . Standard Big Bang nucleosynthesis (BBN) models (e.g., Walker *et al.* 1991) limits  $M/\mathcal{L}_{\text{Bar,BBN}}$  to the range  $(11 - 35)h^{-1}$ . In the region where the cluster and BBN estimates overlap ( $h \geq 0.2$ ),  $M/\mathcal{L}_{\text{Bar}} \sim (35 \pm 6)h^{-1}$ . The dynamical mass-to-light ratios of individual galaxies (Broeils 1992, 1995) range from 4 to 100  $h$ , with 80% of the systems between 6 and 20  $h$ . It is thus possible that the dark halos of individual galaxies consist mainly of non-baryonic dark matter, but a 100% baryonic dark halo is also possible (Gott *et al.* 1974; Briel *et al.* 1992; Rubin 1993; Bahcall 1995; Sackett 1995). It is not clear however where, and in what form, these baryons reside in the galactic halos since all plausible forms of baryonic dark matter seem to be excluded (Hegyi & Olive 1986).

Pfenniger *et al.* (1994) reviewed cold, rotationally supported, molecular hydrogen as a dark matter candidate. In their model, small high density molecular “clumpuscles” form the building blocks of a highly clumped ISM. Their model is best developed in the region beyond the optical disk. The fact that in many galaxies the shape of the rotation curve due to the gas is similar to the observed rotation curve (Bosma 1981; Carignan *et al.* 1990; Carignan & Puche 1990) could then be explained if only 3% - 10% of the gaseous surface density is in atomic form. Such might be expected in the context of clumpuscles hypothesis, or other cold-gas dark matter models (e.g., Gerhard & Silk 1995).

Since the self-gravity of the gas layer beyond the optical disk strongly affects the flaring (Paper I) I investigate whether the clumpuscles hypothesis is consistent with NGC 4244’s flaring curve. Penny Sackett (1995) kindly provided the disk-like surface density distribution inferred from NGC 4244’s rotation curve using a Keplerian as well as a flat extrapolation beyond the last measured point ( $\Sigma_{\text{tot,K}}$  and  $\Sigma_{\text{tot,F}}$ ). We find:  $\Sigma_{\text{DM,K}} \approx 86 \exp(-R/5.2)$ , and  $\Sigma_{\text{DM,F}} \approx 55 \exp(-R/11.4) M_{\odot}\text{pc}^{-2}$ . For NGC 4244, the dark-to-H I surface density is not constant:  $\Sigma_{\text{DM}}/\Sigma_{\text{H I}} \approx 10 \exp((R - 10)/(1.7 \text{ kpc}))$ . Carignan & Puche (1990) found a similar effect for NGC 7793. This contrasts Bosma’s (1981) finding that the dark-to-H I surface density ratio is approximately constant with a value of 3-10%.

The thickness a dark gaseous disk can be calculated when a vertical velocity dispersion is assumed. I find that a dark disk has a thickness equal to the H I layer if the velocity dispersion of the dark disk is 1.1 (1.3) times larger than  $\sigma_{\text{H I}}$ , for  $\Sigma_{\text{DM,K}}$  ( $\Sigma_{\text{DM,F}}$ ). With these dispersions the “Keplerian dark disk” is close to being stable against radial instabilities ( $Q = 0.8 - 1.2$  beyond the stellar disk) while the “Flat dark disk” is unstable ( $Q = 0.8 - 0.3$ ). Here I include a correction factor  $(1 + \frac{2\pi}{R}(\text{FWHM}_{\text{gas,z}}/2.3) \approx 1.3)$  due to the thickness of the disk (e.g., Pfenniger *et al.* 1994). Note that if the dark matter is disk-like, it must have an anisotropic velocity dispersion tensor, which may or may not be the case for clumpuscle-like dark matter.

## 5. Looking Ahead

I have presented the results of a new method to determine the shape of dark matter halos from sensitive H I measurements and careful modeling. The first results exclude neither cold dark matter nor disk-like, baryonic dark matter. With current technology and “reasonable” observing times, the thickness of the H I layer can be measured for galaxies closer than  $\sim 15$  Mpc at inclinations  $\gtrsim 60^\circ$ . I recently observed seven more systems (NGC 2366, 2403, 2903, 2841, 3521, 4236, and 5023) for which I will try to determine the DM halo shapes. Furthermore, the analysis of the flaring of the gas layers of the Milky Way and M31 is in progress. With this increased sample it will be possible to gauge the significance of the highly flattened halo of NGC 4244 and, hopefully, put more stringent constraints on the nature of the dark matter.

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